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DEVICE AND METHOD FOR DETECTING THE PHASE AND AMPLITUDE OF ELECTROMAGNETIC WAVES

BACKGROUND OF THE INVENTION:

The invention concerns an apparatus for detecting the phase and amplitude of electromagnetic waves, more specifically preferably in the optical and in the near infrared and ultraviolet range, comprising at least two modulation photogates which are sensitive to the electromagnetic waves (or photosensitive) and accumulation gates which are associated with the modulation photogates and which are not photosensitive or shaded, and electrical connections for the modulation photogates and the accumulation gates so that the latter can be connected to a reading-out device and the former can be connected to a modulating device, wherein the modulating device increases or reduces the potential of the modulation photogates relative to each other and also relative to the preferably constant potential of the accumulation gates corresponding to a desired modulation function.

Such an apparatus is known by the term 'photomixing detector' (abbreviated as PMD) from German patent applications Nos 196 35 932.5 and 197 04 496.4 and international patent application PCT/DE97/01956 based on the two applications referred to above.

The above-indicated applications are to the same inventor and were filed for the applicant of the present application, and reference is made to the entire disclosure of those previous applications insofar as described therein are the basic mode of operation, performance and possible uses of photomixing detectors. The present invention therefore does not discuss those fundamental functions of photomixing detectors but is concerned primarily with specific configurations and uses of photomixing detectors, by which the elements that are already known are optimised.

By virtue of the inherent mixing procedure which is implemented upon reception of the light which is modulated, reflected or emitted by an

photosensitive detectors, for example in the opto-electronic art and in optical signal transmission.

In addition a higher level of functionality and flexible use of the PMD-pixels and PMD-arrays is desirable for different uses, for example for implementing different modes of operation with the same pixels, in particular for reasons of economy.

SUMMARY OF THE INVENTION:

Having regard to the foregoing, the object of the present invention is to provide an apparatus for detecting the phase and amplitude of electromagnetic waves, having the features set forth in the opening part of this specification, which has a markedly improved band width, in which moreover misinterpretations of light-dark boundaries on imaged surfaces are less probable or even excluded, and with which a higher level of functionality and economy in practical uses is achieved.

That object is attained in that the modulation photogates like also the accumulation gates are provided in the form of long narrow parallel strips in mutually juxtaposed relationship, which group-wise form a PMD-pixel, and wherein the accumulation gates are in the form of reading-out diodes.

The fact that the modulation photogates and the accumulation gates are in the form of narrow long strips and the arrangement thereof in parallel directly mutually juxtaposed relationship results in very short channel lengths for the gates (the modulation gate strip width is referred to as the gate length, from MOS-transistor technology). The free charge carriers produced in or under the modulation photogates drift only transversely with respect to the strip direction by the short distance of the gate length to the adjoining accumulation gate, in which respect that drift is supported by a suitable electrical field on the part of the modulation voltage at the modulation photogates. As a result the drift times fall for example below 1 nanosecond so that accordingly it is possible to achieve a usable modulation band width of 1 GHz. Even if the individual strips of the modulation photogates and also the accumulation gates are relatively

a very inexpensive and well-established technology which permits mass production of corresponding elements and at the same time also allows on-chip and multi-chip module integration of the peripheral electronics such as the evaluation electronics and the modulation electronics.

In CMOS-technology both conventional CMOS-pixels with 2D-functionality (so-called 2D-pixels) and also PMD-pixels with 3D-functionality (so-called 3D-pixels) can be integrated in a linear array or in a matrix array in a mixed configuration. In this case the various, in particular adjacent items of pixel information can be evaluated in a downstream-disposed, data-fusioning and interpolating apparatus, in terms of rapid reconstruction of the complete 3D-color/depth image by means of the items of color information of the 2D-pixels and the 3D-depth and 2D-gray value information of the 3D-PMD-pixels, which affords totally new options in regard to optical measurement procedures and in automation, object identification, security technology and multi-media technology.

BRIEF DESCRIPTION OF THE DRAWINGS:

Further advantages, features and possible uses of the present invention will be apparent from the description hereinafter of preferred embodiments and the accompanying drawings in which:

Figure 1 is a plan view of a pixel of a first embodiment of the present invention,

Figure 2 shows the interconnection of two adjacent pixels,

Figure 3 shows a portion from a view in cross-section through the pixel elements shown in Figure 2, in a section taken along line III-III in Figure 2,

Figure 4 is a plan view on an enlarged scale of a portion of the double pixel or 2-quadrant pixel shown in Figure 2,

Figure 5 is a view in section transversely to the strip direction through a pixel in another embodiment of the present invention with in each case three modulation photogates between two respective

accumulation gates and a buried n-layer and with modulation photogate electrodes embedded in the insulating material,

Figure 6 is a plan view of the 3-gate structure of a PMD-pixel in a multi-strip technology as shown in Figure 5 in a view corresponding to Figure 4,

Figure 7 is a perspective view of a portion of the pixel shown in Figures 5 and 6,

Figure 8 shows four pixel elements which are connected together with different strip orientations and which form a pixel unit for various modes of operation,

Figure 9 shows a field comprising 2 x 4 pixels as shown in Figure 8,

Figure 10 diagrammatically shows the mode of operation of a 3D-camera which is constructed from a relatively large field of pixel elements similarly to Figure 9,

Figure 11 shows an optical PLL-circuit or DLL-circuit on a PMD basis for light barriers, time lapse or delay cameras and data light barriers with optional data signal regeneration, and

Figure 12 shows a login amplifier circuit for measuring in-phase and quadrature signals and signals with band spread technology in particular for high-sensitivity data light barriers, for phase transit time measurements and for optical data transmission preferably in optical CDMA (Code Division Multiple Access) systems and with optional data signal regeneration.

DETAILED DESCRIPTION OF THE INVENTION:

Shown in the middle part of Figure 1 is a row of parallel vertical strips, wherein the light strips reproduce photosensitive, semitransparent modulation photogates while the dark strips which are identified by references 4 and 5 correspond to light-opaquely covered accumulation gates or reading-out gates. The narrow black vertical strips represent insulating separating surfaces between adjacent modulation photogates 1 and 2.

their potential in accordance with the modulation function. That results in a generally flattened potential configuration and a still better channel separation effect, a higher drift speed and a lower level of modulation power.

In this respect, Figure 5 is a view in section similarly to Figure 3, but without the pixel 20 in this case being divided into a plurality of portions. Figure 5 illustrates an advantageous configuration with a buried n-layer and with modulation gate electrodes which are embedded in the insulating material, which is advantageous for very small structures, in comparison with overlapping gate structures. Figure 6 shows a view of the PMD-pixel 20 from above similarly to Figure 4 and Fiaure 7 shows a perspective view of this photomixing detector PMD.

Figure 8 shows four pixel elements which are composed of strip-shaped modulation photogates and accumulation gates and which are each of a substantially square shape and which are assembled to form a pixel which is once again square overall, wherein the strips in the quadrants which are arranged in diagonal relationship with each other respectively extend parallel to each other while they extend perpendicularly to each other between adjacent quadrants. That substantially suppresses mutual overcoupling and falsification of different adjacent modulation signals. In that arrangement the evaluation circuits are moved to those sides of the square which can be arranged outside the square pixel surface. In this case also modulation of the modulation photogates is preferably again effected with a modulation voltage signal which, for two quadrants in mutually diagonal relationship, relative to the other two diagonally arranged quadrants, is phase-shifted through 90° or is delayed by a chip width $T_{ch,p}$ in the case of PM-modulation, which in turn results in simultaneous measurement of in-phase and quadrature signals. The modulation voltage lines which overlap at the center can be closed for 1-quadrant operation, for 2-quadrant operation they can be only-horizontally and vertically connected and for separate 4-quadrant

light signal is therefore correlated twice per pixel with the same modulation function by means of the modulation photogates so that that entails transit time information and thus also spacing information of individual elements of the surface of the object 7.

In the case of the configuration according to the invention, in the form of long narrow strips, those items of depth information are no longer misinterpreted by virtue of light-dark boundaries on the surface of the object 7.

Figures 11 and 12 show the use of corresponding PMD-elements in the highly sensitive reception of optical signals by means of phase regulating circuits, PLL and DLL.

Figure 11 shows an optical PLL-circuit or DLL-circuit with a PMD-pixel 10 as electro-optical mixing element which has a very high level of sensitivity as can advantageously be used in light barrier arrangements, as a PLL-array in time-lapse cameras, in optical remote controls and in data light barrier assemblies as well as for the regeneration of data signals in optical communications. An optical PMD-PLL can be highly integrated as the usual reception -HF-amplifier which is connected downstream of the photodiode and the electronic mixer are completely eliminated because the photomixing detector PMD with the reading-out circuit 31 at the output 34 already provides the mixed product in the low frequency range in the form of a low pass-filtered difference signal U_Δ - const $\cdot$ ($i_a - i_b$). The phase regulating circuit is connected by way of a loop filter or a digital regulator 22.

It can be used for many modulation modes, for example for sine, rectangular, frequency, phase modulation and for code multiplexing, for example PN-encoding. In that case the voltage-controlled generator 33 is set to the clock rate and modulation to be received. When the phase regulating circuit is latched data signals which in the case of the wide-band PMD according to the invention occur at a wide-band sum output 35 of the reading-out circuit 31 or by way of a wide-band photodiode with

amplifier, which is operated in parallel with the same optical data signal, can be regenerated with a 1/0-decision element 32 by virtue of clock recovery of that kind. For that purpose the optical 1/0-data signals are preferably encoded as return-to-zero (RZ)-signals.

Figure 12 shows a 2Q-PMD-DLL with which even higher levels of sensitivity can be achieved on the basis of an IQ-PMD-receiver, in particular with PN-modulation 11.

As in the above-mentioned patent applications to the same applicant, which form the basis for this patent application, periodic PN-modulation 11 affords great advantages in terms of PMD-reception, in particular the possibility of multi-channel selectivity, multi-target detection and the highest degree of sensitivity in respect of phase transit time resolution. In accordance with the invention it is also possible to use PN-encoded data signals for data light barrier arrangements inclusive of distance measurement and for optical CDMA-data transmission, for example, as shown in Figure 12. In that respect for example a logic '1' corresponds to a normal PN-word whereas a logic '0' corresponds to the inverted PN-word = $\overline{PN}$, that is to say the light/dark chips are interchanged. In contrast to Figure 11, in Figure 12 the outputs from the summing and difference amplifier 41 are both connected to the loop filter 22 which then feeds the VCM f_{chip} 44 connected to the PN-modulation generator 11. It is the difference output voltage that is formed as the difference of the quantitative differences of the photocurrents: $U_\Delta = const \cdot (| i_a - i_b | - | i_c - i_d |)$. By means of the recovered word clock it is possible to regenerate the data signal of the PN-encoded 1/0-data sequence by a procedure whereby in the summing amplifier the sum 45 of the differences of the photocurrents $U_\Sigma = const \cdot (| i_a - i_b | - | i_c - i_d |)$ is respectively formed by way of a PN-word length by means of a short-term integrator contained in the summing amplifier 41 and in the 1/0-decision element 42 the 1/0-decision is taken in clock-synchronous manner for subsequent evaluation or regeneration.

With a VCO providing a sine modulation for the modulation 11 voltage and with the circuit element 30 where T_{chip} = T/4 of the sine period, it is also possible to detect and regenerate vector modulation.